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Enhanced Performance Stabilization Increases Performance Variability in a Virtual Interception Task

Crislaine Rangel Couto[1,2], Claudio Manoel Ferreira Leite[3], Carlos Eduardo Campos[1,4], Leonardo Luiz Portes[5], Suziane Peixoto dos Santos[6], Madson Pereira Cruz[1], Maria Carolina Andrade Sousa[1], and Herbert Ugrinowitsch[1]

Abstract

Performing a motor task depends on the level of performance stabilization and movement control, and both aspects of motor behavior are related to motor learning (retention and transfer) and adaptation (predictable and unpredictable perturbations). Yet few studies have further investigated the underlying dynamics that may elicit these benefits. In this study, we investigated the effects of two levels of performance stabilization on motor performance and control while learning to intercept a virtual moving target. We randomly divided 40 participants of both sexes

[1]Sports Department, Universidade Federal de Minas Gerais
[2]Bioscience Department, Centro Universitário Izabela Hendrix, Belo Horizonte, Brazil
[3]Department of Physical Education and Health Sciences, Universidade Federal de São João del-Rei
[4]Department of Physical Education, Universidade de Itaúna
[5]Department of Mathematics and Statistics, University of Western Australia
[6]Department of Sports Science, Universidade Federal do Triângulo Mineiro, Uberaba, Brazil

Corresponding Author:
Herbert Ugrinowitsch, Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte, Minas Gerais, CEP 31270-901, Brazil.
Email: herbertu@ufmg.br

($M_{age} = 26.02$ years, $SD = 2.02$) into a Stabilization Group (SG) and a Superstabilization Group (SSG). We considered the performance stabilized when a moving target was intercepted three times in a row and superstabilized when the same criterion was repeated six times. We analyzed outcome variables related to performance accuracy (absolute spatial error) and variability(coefficient of variation) and motor control (relative time to peak velocity-tPV% and its coefficient of variation) on both the first and last blocks of practice trials. Both groups showed comparable increases in performance accuracy from the first to the last block ($p = .001$, $\eta_p^2 = 1.00$), but SSG presented higher variability than SG ($p = .05$, $\eta_p^2 = .70$). Concerning motor control, both groups started the experiment with low tPV% and finished with comparably high tPV% and variability. Thus, although practicing two levels of performance stabilization led to similar performance accuracy and movement control, superstabilization resulted in higher performance variability with no loss of accuracy. Enhanced stabilization may increase the ability to adapt to environmental changes, but more research is needed to demonstrate this. These findings add to an understanding of the relationship between levels of performance stabilization and performance variability and may have implications for professional interventions (e.g. sports, rehabilitation) in considering the benefits of practice beyond performance stabilization.

Keywords
stabilization of performance, variability, interception task, moving target, motor skill

Introduction

The accurate interception of a moving object requires organizing the movement correctly in time and space, and this motor skill demand is common for activities of daily living (Marinovic & Wallis, 2011) and in sports performance (Breen, 1967; Tresilian, 2004). Interception tasks demand the correct application of appropriate information (Tresilian et al., 2004) for the interceptor and the target object to reach the same location simultaneously (Cunningham et al., 2001; Tresilian et al., 2003). There has been widespread interest in understanding the factors that influence success in interceptive actions, and there have been relatively recent and still increasing numbers of investigations related to the performer's skill level (Caljouw et al., 2005; Corrêa et al., 2015; Ugrinowitsch et al., 2011). Different skill levels have been classified according to the accuracy and certainty within which a specified performance outcome is obtained, referred to as performance stabilization (Fonseca et al., 2012; Santos et al., 2017; Ugrinowitsch et al., 2011).

Ugrinowitsch et al. (2011), for example, observed the effects of three levels of performance stabilization on the adaptation to predictable perturbation in a coincident timing task, which presents similar demands to interceptive actions (Tresilian, 2005). The three levels of stabilization were named: (a) prestabilization when the practice was not enough to stabilize performance; (b) stabilization when the practice led to stabilized and accurate performance; and (c) superstabilization when the practice was extended beyond performance stabilization. The superstabilization level adapted better than other stabililization levels to predictable perturbations in motor skills. Other studies have also found that higher levels of performance stabilization enhance the acquisition of learning and adaptive capacities (Corrêa et al., 2015; Fonseca et al., 2012; Santos et al., 2017; Ugrinowitsch et al., 2011).

The advantage of superstabilization may be related to motor variability (Corrêa et al., 2015; Ugrinowitsch et al., 2014). Certain levels and aspects of motor variability have been interpreted as suitable for motor performance and have been related to motor adaptation and learning (Corrêa et al., 2015; Fonseca et al., 2012; Ugrinowitsch et al., 2014; Wu et al., 2014). More specifically, better adaptation was found in groups with higher levels of stabilization, which have also presented higher movement variability. Thus, variability might play different functions, based on the level of stabilization (Manoel & Connolly, 1995; Tani, 2000; Tani et al., 2014). One thing to note is that while studies on levels of stabilization have investigated its effects on adaptation and learning, they have not paid much attention to the acquisition or practice phase of learning. If the level of stabilization influences performance after practice whether on learning tests (Corrêa et al., 2015) or adaptation phases (Fonseca et al., 2012; Ugrinowitschet al., 2011, 2014), something that occurred within the acquisition phase may have been responsible for these differences and must be separately investigated.

Practice until stabilization reduces variability as control becomes stable, and practice up to superstabilization goes beyond this benefit to enable exploitation of the task (Sutton & Barto, 2017; Wu et al., 2014), leading in turn to increased variability and, ultimately, to more flexible behavior (Corrêa et al., 2015; Ugrinowitsch et al., 2014). A possible explanation for this relationship between the level of stabilization and variability is that the task exploitation elicited by superstabilization may provide an action plan with more information, allowing changes in the mechanisms of control, i.e., both feedforward and online feedback control, permitting a behavioral adjustment to meet task demands (Corrêa et al., 2015; Ugrinowitsch et al., 2014). These mechanisms of control can be inferred by kinematic aspects of the movement such as the velocity curve.

Research on the interception of moving targets shows that the velocity profile of interceptive actions with one degree of freedom changes with learning, and indicates modifications in the mechanisms of control. During early learning, the

peak velocity is observed at the beginning of the movement, and as the practice continues, peak velocity moves forward and closer to the moment of interception (Tresilian & Plooy, 2006). Such control reflects a strategy of waiting for the target to be as near as possible to the strike zone before starting the interception action; the same strategy has been adopted by professional baseball players (Breen, 1967). However, it is not known whether the control strategy used during the interception of moving targets may be modified by the level of stabilization achieved during motor skill acquisition or whether this control strategy is a constant constraint on this kind of task such that performance variability may be due to neuromotor factors (Haddad et al., 2005) other than control mechanisms.

Thus, in this study, we sought to investigate the influence of two levels of performance stabilization on the variability of performance and motor control when learning a virtual interception task. Based on earlier research, as described above, we expected superstabilization to elicit higher performance variability than stabilization. As for the mechanisms of control, we expected similar motor control strategies between stabilization and superstabilization groups, since the feedforward factor seems inherent to this kind of task.

Method

Participants

We tested 40 university students (22 men and 18 women, $M_{\text{age}} = 26.02$ years, $SD = 2.02$), each of whom gave written informed consent to participate in this study. All participants were healthy and self-declared a right-handed preference and normal or corrected-to-normal vision. The Institutional Review Board of the University approved this study (ETIC 0563.0.203.000-10).

Instruments and Task

The instruments used were an Intel Celeron 2.20 GHz computer, a 17 " monitor (Dell 60 Hz, 1366×768'), a 35 cm long digital tablet with a wireless pressure sensitive device (WACON- INTUOS 3 – 9×12) with a capture frequency of 200 Hz, a digital pen (INTUOS 3) compatible with the tablet and a projector to project the virtual interception task onto a 304 cm wide and 228 cm high white screen placed 370 cm in front of the participant. The virtual interception task (VIT: Leonardo Portes, Crislaine Rangel & Herbert Ugrinowitsch, UFMG, Belo Horizonte, Brazil), data acquisition, and data processing were controlled by the software VIT developed in a Labview® environment (National Instruments Corporation, Austin/TX, USA). Fixed on top of the tablet, and with the same measures of it, was a 2 cm high foaming plate made of Ethylene-

vinyl acetate (EVA) with a posterior-anterior cut in its center (27.7 cm long and 1.7 cm wide) forming a groove to constrain the movement of the digital pen within one degree of freedom. The width of the groove was just enough to fit the pen and allow it to slide on the digital tablet along the groove.

To perform the VIT, illustrated in Figure 1, participants sat on a chair next to the digital tablet that was placed on a support at the right side of the participants at the height of their elbow. The participants were requested to intercept a virtual moving target (4×6 cm yellow rectangle) using a virtual effector (2×4 cm green rectangle) within the width of the target and inside the limits of the strike zone. From the first appearance on the right side of the participant, the virtual target traveled 213 cm from the right to left of a virtual rail at a constant velocity of 145 cm.s^{-1} until reaching the center of the strike zone. The virtual effector moved on a virtual rail perpendicular to the target rail, and the participant physically controlled it with the digital pen by moving the pen horizontally forward on the digital tablet along the groove.

Participants were told to perform the interceptive action within a 200–250 ms Movement Time (MT). We chose the time window of 200–250 ms because it

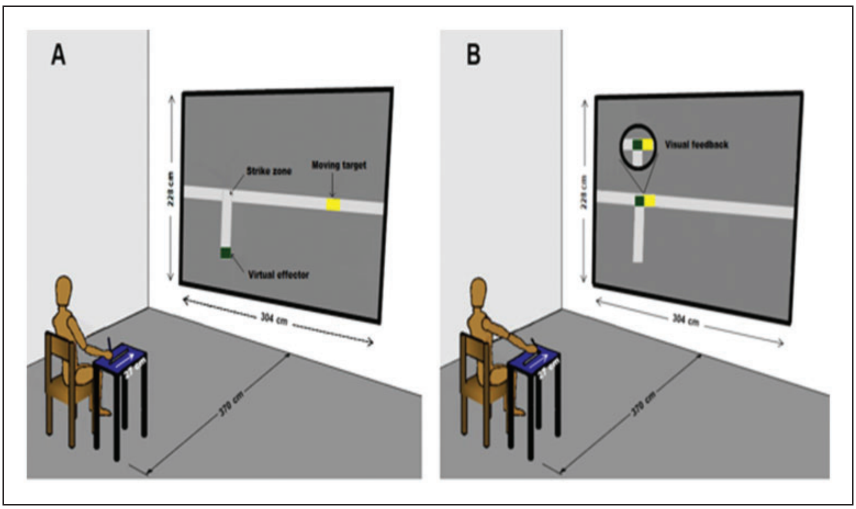

Figure 1. Illustrations of the Virtual Interception Task (VIT) Representing the Physical (Chair, Table, Digital Tablet, and Digital Pen), and the Virtual (Rails, Striking Zone, Virtual Moving Target, and Virtual Effector) Elements. Dimensions are not to scale. A: Initial position and elements presented on the screen. Virtual moving target (4 x 6 cm yellow rectangle) virtual effector (2 x 4 cm green rectangle); the strike zone was the intersection of the rails for the target and the effector. B: End position and visual feedback. The digital pen was moved forward along the EVA groove in the center of the digital tablet. The zoomed detail represents the visual feedback available to the participant after each trial. In this particular case, it represents a miss caused by "early" action.

characterized a ballistic movement and provided time to make corrections after the movement's onset (Marinovic & Wallis, 2011), enabling us to identify the use of feedforward or online feedback control.

Procedure

We randomly divided the 40 participants into two groups that were balanced by sex – a stabilization group (SG) and a superstabilization group (SSG). Both groups practiced the task until they reached the predefined criterion of stabilization. These criteria represented two different skill levels. The SG practiced until reaching the performance criterion of intercepting the virtual target three times in a row with errors between -5 and $+5$ cm within 200 attempts, and the SSG practiced until completing the same criterion for six times within 350 attempts. We excluded and substituted three participants from the original sample (one from SG and two from SSG) because they failed to reach the performance criterion. The participants were informed that they could request a rest interval of up to one minute when they felt tired or fatigued.

The practice session started with a five-trials demonstration provided by an expert model, followed by verbal instructions. Participants received knowledge of results (KR) about their performance and their MT after each practice trial. KR about the performance guided learning and consisted of a screenshot showing the position of the virtual target and the effector at the time the effector reached the strike zone (Figure 1B). KR about the MT was applied to help participants perform the movement in the specified range of 200–250 ms and consisted of qualitative information corresponding to specific MT bandwidths as follows: (a) MTs below 179 ms – "the movement was very fast;" (b) MTs between 180 and 199 ms – "the movement was fast;" (c) MTs between 200–250 ms – "good movement time; " (d) MTs between 251–270 ms – "the movement was slow; " and (e) MTs over 271 ms – "the movement was very slow". The experiment finished when the participant reached the stabilization criterion specific to his/her group.

Data Analysis

We ran data analyses with the Statistica 10.0 software package. Quantitative variables were expressed as means and standard deviations. To verify possible differences between the SG and SPG associated with the two levels of stabilization at the beginning and end of the experiment, we ran a two-way (2 groups $\times 2$ blocks) analysis of variance (ANOVA) on the first three and the last three attempts. We performed post-hoc tests using Duncan's test for pair comparisons. We set statistical significance at $p < 0.05$. The variables analyzed were (a) absolute spatial error(AE) (cm); (b) coefficient of variation (CV) of the absolute error (cm), defined as the standard deviation divided by the mean of the absolute

Table 1. Mean (M) and Standard Deviation (SD) of Absolute Error (AE) and Time Relative to Peak of Velocity (tPV%) to Superstabilization Group (SSG) and Stabilization Group (SG).

	AE		AE		tPV%		tPV%	
	First block		Last block		First block		Last block	
Groups	M	SD	M	SD	M	SD	M	SD
SSG	16.99	14.88	1.87	1.55	56.75	11.66	66.12	9.65
SG	18.58	11.98	1.98	1.05	55.2	12.67	64.4	8.86

error)×100; (c) relative time to peak velocity (tPV) (%), defined as (tPV/total movement time)*100; and (d) the coefficient of variation of the relative time to peak velocity (%). The absolute error was calculated as the distance between the center of the target and the center of the effector. The tPV was analyzed as a percentage of the movement time because both can change from trial to trial. To test the normality of the data distribution, we used the Shapiro–Wilk test. Effect sizes are expressed as partial eta square ($\eta_p{}^2$) and effects were considered large when $\eta_p{}^2$ was above .14; medium for $\eta_p{}^2$ between .06 and .14; small for $\eta_p{}^2$ between .01 and .06; and trivial when $\eta_p{}^2$ was below .01 (Cohen, 1988).

Results

Table 1 shows the mean and standard deviation values of the absolute error and tPV% in the first and last block of practice for SG and SSG.

The Shapiro–Wilk test indicated that all data were normally distributed ($p \leq .97$); we followed with the parametric statistics. Figure 2A shows that there was a significant main effect for blocks on performance accuracy $F(1,38) = 93.30$, $p = .001$, $\eta_p^2 = 1.00$, with accuracy having increased from the beginning of practice to the moment the specific performance criteria were reached. There were neither a significant main effect for groups $F(1,38) = .08$, $p = .77$, $\eta_p^2 = .50$ nor a significant group by block interaction $F(1, 38) = .06$, $p = .80$, $\eta_p^2 = .20$ for accuracy.

Figure 2B shows that there was a significant main effect on performance variability for groups, $F(1, 38) = 3.91$, $p = .05$, $\eta_p^2 = .70$, and the SSG was more variable than the SG. As the confidence interval indicated a difference between the groups in the last block, we ran a *t*-test in this block and confirmed the higher variability of SSG ($p = .001$). There were neither a significant main effect for blocks, $F(1, 38) = 1.99$, $p = .16$, $\eta_p^2 = .50$ nor a significant interaction effect, $F(1, 38) = .32$, $p = .57$, $\eta_p^2 = .60$.

Figure 3A shows that there was a significant main effect for blocks on control strategy (tPV%), $F(1, 38) = 14.56$, $p = .001$, $\eta_p^2 = .90$, with an increase in

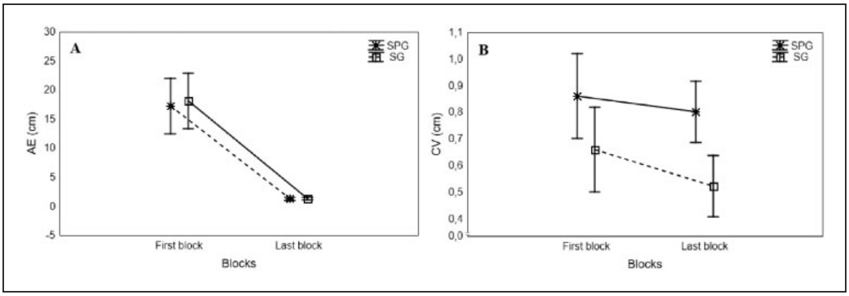

Figure 2. Performance of the Stabilization (SG) and Superstabilization (SSG) Groups in the First and Last Blocks of Practice. A: Absolute spatial error (AE). (*) different from the first block ($p \leq .05$). B: Coefficient of variation of the AE (CV). (+) difference between groups ($p \leq .05$). Spread bars in both graphs correspond to 95% confidence interval.

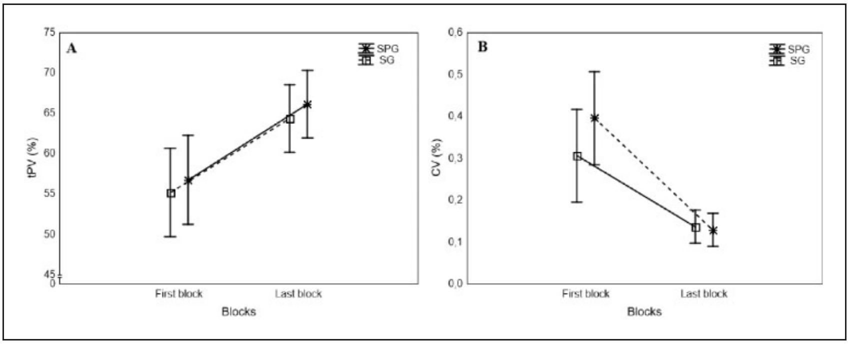

Figure 3. Velocity Profile of the Stabilization (SG) and Superstabilization Groups (SSG) in the First and Last Blocks of Practice. A: Relative time to peak of velocity (tPV%). (*) different from the first block ($p \leq .05$). B: Coefficient of variation of tPV% (CV). (*) different from the first block ($p \leq .05$). Spread bars in both graphs correspond to 95% confidence interval.

control strategy (tPV%) from the beginning of practice to the moment the specific performance criteria was reached. There were neither a significant main effect for groups, $F(1,\ 38) = .46$, $p = .49$, $\eta_p^2 = .4$ nor a significant interaction effect $F(1,\ 38) = .001$, $p = .97$, $\eta_p^2 = .40$.

Figure 3B shows that there was a significant main effect for blocks, $F(1,\ 38) = 27.48$, $p = .001$, $\eta_p^2 = .90$, on variability in the relative time to peak velocity (CV %), with a decrease in variability from the beginning of practice to the moment the specific performance criteria were reached. There were neither a significant effect for between groups, $F(1,\ 38) = 1.04$, $p = .31$, $\eta_p^2 = .10$ nor a significant interaction, $F(1,\ 38) = 1.37$, $p = .24$, $\eta_p^2 = .20$.

Discussion

The purpose of the present study was to investigate the influence of performance stabilization and superstabilization on performance and motor control variability when learning a virtual interception task. Based on prior research, we expected that the superstabilization group would present higher performance variability (Corrêa et al., 2015; Fonseca et al., 2012; Ugrinowitsch et al., 2014), while other motor control variables would not differ between the groups (Tresilian & Plooy, 2006), and our findings confirmed these hypotheses.

At the beginning of practice, stabilization and superstabilization had low accuracy, and participant groups did not differ. However, in the last practice block, stabilization and superstabilization groups both showed improved performance accuracy, again with no between-group difference. This accuracy result was due to our having set specific accuracy performance criteria in order for each group to reach specified levels of stabilization. Previous studies adopted a specific number of attempts during the learning phase and then analyzed performance variability (Diedrichsen & Kornysheva, 2015; Haddad et al., 2005; Wu et al., 2014). Consequently, the variability observed in these studies may have been influenced by individual differences as participants achieved different results at the end of practice.

Our use of standardized performance criteria allowed all the participants to reach the same skill level (Fonseca et al., 2012; Santos et al., 2017; Ugrinowitsch et al., 2014), adding the reliability of our findings. Since participants only finished the practice phase when they reached performance criteria(e.g., intercept the target three trials in a row for the SG), we did not expect performance accuracy differences between groups, even with the differences between SG and SSG criteria. Moreover, as a successful target hit did not require a specific point but rather a bandwidth (target size and strike zone), participants were able to show performance variability within the bandwidth. We followed this methodological procedure and, based on results from prior studies (Corrêa et al., 2015; Ugrinowitsch et al., 2014), we expected group differences in favor of the superstabilization group on performance variability, which was our hypothesis.

At the beginning of the practice, stabilization and superstabilization groups had comparable variability (CV); and, as in other studies (Haddad et al., 2005; Santos et al., 2017), variability was reduced from the beginning to the end of the practice phase. Moreover, at the end of practice, the superstabilization group achieved higher performance variability than the stabilization group, confirming our hypothesis. This is particularly interesting because the groups showed no accuracy differences at the end of practice. Analyzing accuracy and variability data collectively, we found that practicing to the point of performance stabilization led the SG to increase performance accuracy and decrease variability while practicing beyond performance stabilization to a point of superstabilization led the SSG to demonstrate increases in performance variability, relative to

the SG. This varied performance pattern between SG and SSG groups may indicate the exploration and exploitation processes during motor learning (Sutton & Barto, 2017; Wu et al., 2014). The decrease in response variability due to stabilization may indicate that stabilization learners explored the task characteristics that influenced performance variability and learned or achieved a more efficient movement pattern. However, as practice continued for superstabilization learners, they began to exploit their understanding of task-related movement patterns and experiment with variations further variations that led to show increased performance variability. This behavior also supports a functional role for motor variability (Manoel & Connolly, 1995; Tani, 2000; Tani et al., 2014).

When we relate performance variability to movement control, we might consider that, at the beginning of practice, the variability in movement output is high because no specific action plan yet controls movement (Tani et al., 2014). Instead, movement is then controlled predominantly by online feedback mechanisms (Elliott et al., 1999; Tresilian, 1995). Practice until stabilization builds a spatiotemporal pattern of movement from which one can infer an action plan for movement control, and this added control, in turn, reduces output variability (Tani et al., 2014). At this moment, movement control changes predominantly to feedforward mechanisms (Elliott et al., 1999).

In the present study, we adopted tPV% as a motor control mechanism measure to identify the moment of the PV within the total movement time. We expected tPV% to increase because the strategy, in this kind of task, is to reach tPV close to the end of the movement (Tresilian & Plooy, 2006). In this case, the neuromotor system prepares the movement in advance and uses the mechanism of feedforward control to execute it. It seems that the neuromotor system learns to wait and initiate the movement when the target is close to the strike zone (Marinovic & Wallis, 2011; Tresilian & Plooy, 2006). Our results presented this same pattern and indicated that, despite the differences in performance variability between groups with two levels of stabilization, there was no group difference in the control strategy.

These results indicate that interception is controlled via feedforward mechanisms, for both participant groups – those who trained tostabilization and superstabilization.Thus, it seems that the matter of performance variability will not prove to be related to the mechanisms of movement control but to some other neuromotor variable (Benda et al., 2000; Haddad et al., 2005). Although variability is a characteristic of human behavior (Bernstein, 1967), it may have different sources (Benda et al., 2000; Haddad et al., 2005). Future studies might use different measures such as neuromuscular variables (e.g., electromyography) in an attempt to identify the source of performance variability.

Most notably, this is the first study to investigate and identify higher performance variability during the acquisition learning phase when practice goes beyond performance stabilization (i.e., to superstabilization). When investigated

in past adaptation studies, performance variability has been related to adaptability to environmental changes (Santos et al., 2017; Ugrinowitsch et al., 2014). However, we still do not know if and how variability within the acquisition phase improves adaptations in interceptive tasks. Thus, a follow-up study is underway in our laboratory to explore potential answers to this question. Meanwhile, a theoretical and practical implication of the results of this study and those of Ugrinowitsch et al. (2014), is a newfound importance to movement variability when extending motor learning practices to reach expertise. For example, to further assist a highly skilled performer, rather than striving to minimize performance variability, attention might be given to maintaining accuracy without restricting variability. Practice until superstabilization appears to have achieved both of these characteristics, and further investigating this relationship remains a challenge for future studies.

Ethical Approval

This research was performed following the ethical standards established in the 1964 Declaration of Helsinki, amended in 1989, and was approved by the Local Ethics Committee (n. 0563.0.203.000-10).

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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ORCID iDs

Crislaine Rangel Couto https://orcid.org/0000-0003-3305-3208
Leonardo Luiz Portes https://orcid.org/0000-0002-4310-2942
Madson Pereira Cruz https://orcid.org/0000-0002-2078-5496
Herbert Ugrinowitsch https://orcid.org/0000-0003-0317-1940

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Author Biographies

Crislaine Rangel Couto: Graduation in Physical Education, Master and PhD in Sports Sciences. Actually is Professor at Centro Universitário Metodista Izabela Hendrix.

Claudio Manoel Ferreira Leite: Graduation in Physical Education, Master and PhD in Sports Sciences. Actually is Assistant Professor at Universidade Federal de São João del-Rey.

Carlos Eduardo Campos: Graduation in Physical Education, Master and PhD in Sports Sciences. Actually is Assistant Professor at Universidade de Itauna.

Leonardo Luiz Portes: Graduation in Physics, Master in Physics and PhD in Sports Sciences. Actually is Research Fellow at The University of Western Australia.

Suziane Peixoto dos Santos: Graduation in Physical Education, Master and PhD in Sports Sciences. Actually is Adjunt Professor at the Federal University of Triangulo Mineiro.

Madson Pereira Cruz: Graduation in Physical Education and Master in Sports Sciences. Actually is PhD student in Sports Sciences at Universidade Federal de Minas Gerais.

Maria Carolina Andrade Sousa: Graduation in Physical Education. Actually is teacher at Elementary/High School Santa Marcelina.

Herbert Ugrinowitsch: Graduation in Physical Education, Master and PhD in Physical Education. Actually is Associate professor at Universidade Federal de Minas Gerais.